Is there a unique thermal source of dileptons in Pb(158 A·GeV) + Au, Pb reactions?

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Abstract

An analysis of the dilepton measurements in the reactions Pb(158 A·GeV) + Au, Pb points to a unique thermal source contributing to the invariant mass and transverse momentum spectra. Effects of the flow pattern are discussed.

Introduction: Dileptons are penetrating probes which carry nearly undisturbed information about early, hot and dense matter stages in relativistic heavy-ion collisions. Some effort, however, is needed for disentangling the various sources contributing to the observed yields and for identifying the messengers from primordial states of strongly interacting matter.

The dielectron spectra for the reaction Pb(158 A·GeV) + Au measured by the CERES collaboration [1] cannot be described by a superposition of e^+e^- decay channels of final hadrons, i.e. the hadronic cocktail. A significant additional source of dielectrons must be there. Since the data [1] cover mainly the invariant mass range $M < 1.5$ GeV the downward extrapolation of the Drell-Yan process is not an appropriate explanation. Also correlated semileptonic decays of open charm mesons have been excluded [2]. As a widely accepted explanation, a thermal source is found to account for the data (cf. [3, 4] and further references therein, in particular with respect to in-medium effects and chiral symmetry restoration).

Very similar, the NA50 collaboration has found, for the reaction Pb(158 A·GeV) + Pb, that the superposition of Drell-Yan dimuons and open charm decays does not explain the data in the invariant mass range 1.5 GeV $< M <$ 2.5 GeV [5]. Final state interactions [6] or abnormal charm enhancement [5, 7] have been proposed as possible explanations. Here we try to explain the NA50 measurements by a more apparent idea [8, 9], namely a thermal source. We present a schematic model which at the same time describes the

CERES and NA50 data.

The model: Since we include the corresponding detector acceptances a good starting point for Monte Carlo simulations is the differential dilepton spectrum

$$\frac{dN}{p_{\perp\,1}\, dp_{\perp\,1}\, p_{\perp\,2}\, dp_{\perp\,2} dy_1\, dy_2\, d\phi_1\, d\phi_2} = \int d^4Q\, d^4x\, \frac{dR}{d^4Q\, d^4x} \delta^{(4)}(Q - p_1 - p_2), \tag{1}$$

where $Q = p_1 + p_2$ is the pair four-momentum, $p_{1,2}$ are the individual lepton four-momenta composed of transverse momenta $p_{\perp\,1,2}$ and rapidities $y_{1,2}$ and azimuthal angles $\phi_{1,2}$. Here we extensively employ the quark - hadron duality [4, 9] and base the rate R on the lowest-order quark - antiquark ($q\bar{q}$) annihilation rate (cf. [10, 11])

$$\frac{dR}{d^4Q\, d^4x} = \frac{5\alpha^2}{36\pi^4} \exp\left\{ -\frac{u \cdot Q}{T} \right\}, \tag{2}$$

where $u(x)$ is the four-velocity of the medium depending on the space-time as also the temperature $T(x)$ does. Note that, due to Lorentz invariance, u necessarily enters this expression. The above rate is in Boltzmann approximation, and a term related to the chemical potential is suppressed. As shown in [4] the $q\bar{q}$ rate deviates from the hadronic one at $M < 300$ MeV, but in this range the Dalitz decays dominate anyhow; in addition, in this range the thermal yield is strongly suppressed by the CERES acceptance. In the kinematical regions we consider below, the lepton masses can be neglected.

Performing the space-time and momentum integrations in eqs. (1, 2) one gets

$$\frac{dN}{dp_{\perp\,1}\, dp_{\perp\,2} dy_1\, dy_2\, d\phi_1\, d\phi_2} = \frac{5\alpha^2}{72\pi^5} p_{\perp\,1} p_{\perp\,2} \int_{t_i}^{t_f} dt\, V(t)\, E, \tag{3}$$

$$E = \begin{cases} \exp\left\{ -\frac{M_\perp \cosh Y \cosh \rho(r,t)}{T(r,t)} \right\} \frac{\sinh \xi}{\xi} & \text{for} \quad 3D, \\ K_0\left(\frac{M_\perp \cosh \rho(r,t)}{T(r,t)} \right) I_0\left(\frac{Q_\perp \sinh \rho(r,t)}{T(r,t)} \right) & \text{for} \quad 2D, \end{cases} \tag{4}$$

$$V(t) = \begin{cases} 4\pi \int dr\, r^2 & \text{for} \quad 3D, \\ t \int dr\, r & \text{for} \quad 2D, \end{cases} \tag{5}$$

where $V(t)$ acts on E, and $3D$ means spherical symmetric expansion, while $2D$ denotes the case of longitudinal boost-invariant and cylinder-symmetrical transverse expansion; the quantity ξ is defined as $\xi = T^{-1} \sinh \rho \sqrt{M_\perp^2 \cosh Y^2 - M^2}$, and $\rho(r,t)$ is the radial or transverse expansion rapidity; K_0 and I_0 are Bessel functions [10]. The components of the lepton pair four-momentum $Q = (M_\perp \cosh Y, M_\perp \sinh Y, \vec{Q}_\perp)$ are related to the individual lepton momenta via

$$M_\perp^2 = p_{\perp\,1}^2 + p_{\perp\,2}^2 + 2 p_{\perp\,1} p_{\perp\,2} \cosh(y_1 - y_2), \tag{6}$$

$$\vec{Q}_\perp = \vec{p}_{\perp\,1} + \vec{p}_{\perp\,2}, \tag{7}$$

$$M^2 = M_\perp^2 - Q_\perp^2, \tag{8}$$

$$\tanh Y = \frac{p_{\perp 1}\, \sinh y_1 + p_{\perp 2}\, \sinh y_2}{p_{\perp 1}\, \cosh y_1 + p_{\perp 2}\, \cosh y_2}. \tag{9}$$

It turns out that the shape of the invariant mass spectrum $dN/(dM\,dY|_{|Y|<0.5}\,dt\,dV(t))$, which is determined only by the emissivity function E, does not depend on the flow rapidity ρ in the 2D case [10], and in the 3D case for $T = 120 \cdots 220$ MeV and $\rho < 0.6$ there is also no effect of the flow. The analysis of transverse momentum spectra of various hadrons species point to an average transverse expansion velocity $\bar{v}_\perp \approx 0.43$ [12] at kinetic freeze-out, while a combined analysis of hadron spectra including HBT data yields $\bar{v}_\perp \approx 0.55$ [13]. Therefore, $\rho < 0.6$ is the relevant range for the considered reactions.

We note further that the invariant mass spectra $dN/(dM\,dY|_{|Y|<0.5}\,dt\,dV(t))$ for the 3D and 2D cases differ only marginally. Relying on these findings one can approximate the emissivity function E by that of a "static" source at midrapidity, as appropriate only for symmetric systems,

$$E = \exp\left\{-\frac{M_\perp \cosh Y}{T(t)}\right\}, \tag{10}$$

thus getting rid of the peculiarities of the flow pattern. In contrast to the invariant mass spectra, the transverse momentum or transverse mass spectra are sensitive to the flow pattern [10, 14, 15], in general. A value of $\rho = 0.4$, for example, causes already a sizeable change of the shape of the spectra $dN/(dQ_\perp dY|_{|y|<0.5}\,dt\,dV(t))$ compared to $\rho = 0$, in particular in the large-$Q_\perp$ region. The differences between the 2D and 3D cases are not larger than a factor of 2 and, in a restricted $Q_\perp$ interval, can be absorbed in a renormalization. The most striking difference of the 2D and 3D scenarios is seen in the rapidity spectrum: for 2D it is flat, while in the 3D case it is localized at midrapidity (values of $\rho < 0.6$ also do not change the latter rapidity distribution). Below we shall discuss which space is left to extract from the dilepton data in restricted acceptance regions hints for the flow pattern when the other dilepton sources are also taken into account.

Comparison with data: In line with the above arguments we base our rate calculations on eqs. (3, 10) and use the parameterizations [16]

$$T = (T_i - T_\infty)\exp\left\{-\frac{t}{t_2}\right\} + T_\infty, \tag{11}$$

$$V = N\exp\left\{\frac{t}{t_1}\right\}. \tag{12}$$

with $T_i = 210$ MeV, $T_\infty = 110$ MeV, $t_1 = 5$ fm/c, $t_2 = 8$ fm/c, $N = \frac{A+B}{2.5n_0}$ with A, B as mass numbers of the colliding systems and $n_0 = 0.17$ fm^{-3}. We stop the time evolution at $T_f = 130$ MeV.

In fig. 1 we show the comparison with the preliminary CERES data applying the appropriate acceptance [1]. One observes a satisfactory overall agreement of the sum of the hadronic cocktail and the thermal contribution with the data. It is the thermal contribution which fills the hole of the cocktail around $M = 500$ MeV in the invariant mass distribution in fig. 1a. In the mass bin $M = 0.25 \cdots 0.68$ GeV the thermal yield is seen (fig. 1b) to dominate at small values of the transverse momentum $Q_\perp$. In this region of $Q_\perp$ transverse flow effects are not important. The large-$Q_\perp$ spectrum is dominated by the cocktail. For higher-mass bins the thermal yield in the region of the first two data points is nearly as strong as the cocktail and rapidly falls then at larger values of $Q_\perp$ below the cocktail. Therefore, the flow effects turn out to be of minor importance for the present analysis, since within our framework the transverse flow shows up at larger values of $Q_\perp$.

The question now is whether the same thermal source model accounts also for the NA50 data [5]. The available NA50 data are not yet efficiency corrected and the efficiency matrix is not accessible. To have a reference we proceed as follows. According to the detailed analysis [5] of the most central collisions, the shapes of the M and $Q_\perp$ spectra for invariant masses below the J/ψ peak are described by the Drell-Yan yield + 3 $\times$ the yield from correlated semileptonic decays of open charm mesons, both ones generated with PYTHIA [17]. We have checked that our PYTHIA simulations coincide with results of the NA50 collaboration when applying the acceptance cuts. Our K factors are adjusted by a comparison with Drell-Yan data [19] and identified open charm data (cf. [2] for the data compilation). Some confidence in our procedure is gained by correctly reproducing the NA50 interpretation [5] of the NA38 data [18], which are efficiency corrected and which we can directly analyze: the NA38 data are described by the Drell-Yan yield + 1.45 $\times$ the open charm contribution; the absolute normalization is obtained from a fit of the Drell-Yan region beyond the J/ψ.

To get the yield for Pb + Pb collisions from PYTHIA the overlap function $T_{AA} = 31$ mb^{-1} is used. The resulting spectra (within the kinematical cuts for the NA50 acceptance) are displayed in figs. 2a and 2b by open squares. One observes that both the continuum part of the invariant mass spectrum (without the J/ψ contribution) and the transverse momentum spectrum for the mass bin $M = 1.5 \cdots 2.5$ GeV are nicely reproduced by the sum of Drell-Yan, open charm and thermal contributions. The thermal yield dominates again at not too large values of $Q_\perp$ where transverse flow effects can be neglected. Therefore, it seems that from present dilepton measurements the transverse flow can hardly be inferred.

Summary and discussion: In summary we have shown that a very simplified, schematic model for thermal dilepton emission, with parameters adjusted to the CERES data, also accounts for the measurements of the NA50 collaboration. A direct comparison with the NA50 data is not possible as long as the efficiency matrix is not at disposal. Nevertheless, our study points to a common thermal source seen in different phase space regions in the dielectron and dimuon channels. This unifying interpretation of different measurements has to be contrasted with other proposals of explaining the dimuon excess in the invariant mass region $1.5 \cdots 2.5$ GeV either by final state hadronic interactions or an abnormally large open charm production. The latter one, in principle, can be checked experimentally [7], thus improving our understanding of dilepton sources.

Due to the convolution of the local matter emissivity and the space-time history of the whole matter and the general dependence on the flow pattern, it is difficult to decide which type of matter (deconfined or hadron matter) emits really the dileptons. Our model is not aimed at answering this question. Instead, with respect to chiral symmetry restoration, we apply the quark - hadron duality as a convenient way to roughly describe the dilepton emissivity of matter by a $q\bar{q}$ rate, being aware that higher-order QCD processes change this rate [15, 20] (to some extent this might be included in a changed normalization N). In further investigations a more reliable rate together with a more detailed space-time evolution must be attempted and chemical potentials controlling the baryon and pion densities must be included. In this line the model has to be improved before using it for analyzing the dilepton yields in the asymmetric reactions S(200 A·GeV) + X measured by the NA38, HELIOS-3, and CERES collaborations, where also details of the rapidity distribution become important.

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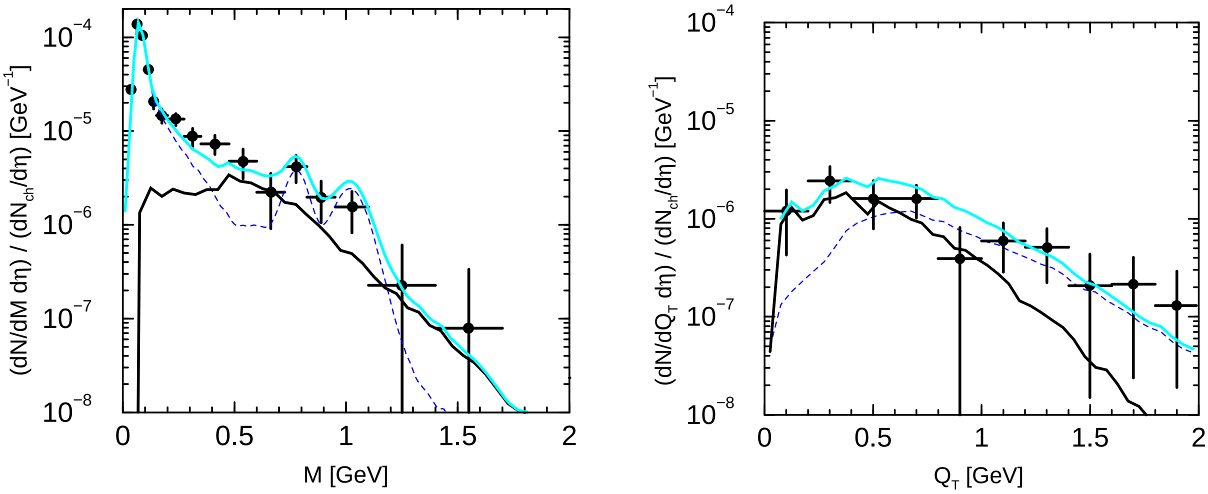

Figure 1: The preliminary CERES data [1] and the hadronic cocktail [1] (dashed lines) and the thermal yield (full curves). The sum of the cocktail and the thermal yield is shown by the gray curves. Left panel (a): the invariant mass spectrum, right panel (b): the transverse momentum spectrum for the mass bin $0.25 \cdots 0.68$ GeV.

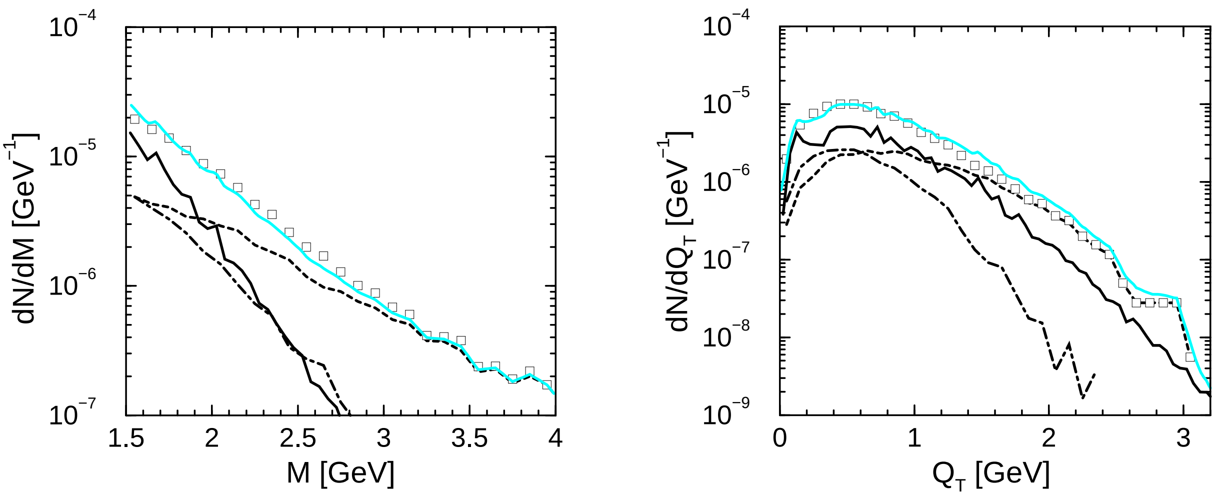

Figure 2: The reconstructed measurements of the NA50 collaboration (see text for details) indicated by open squares (not data!) in comparison with the thermal yield (full curves), the Drell-Yan contribution (dashed curves) and the contribution of open charm decays (dash-dotted curves). The sum of these contributions is displayed by the gray curves. Left panel (a): the continuum invariant mass spectrum, right panel (b): the transverse momentum spectrum for the mass bin $1.5 \cdots 2.5$ GeV.